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S. Abachi et al.
The DØ Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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A Study of the Strong Coupling Constant Using $W+$ Jets Processes

S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B.S. Acharya,[40] I. Adam,[10] D.L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20] J. Alitti,[36] G. Álvarez,[16] G.A. Alves,[8] E. Amidi,[27] N. Amos,[22] E.W. Anderson,[17] S.H. Aronson,[3] R. Astur,[38] R.E. Avery,[29] A. Baden,[21] V. Balamurali,[30] J. Balderston,[14] B. Baldin,[12] J. Bantly,[4] J.F. Bartlett,[12] K. Bazizi,[7] J. Bendich,[20] S.B. Beri,[31] I. Bertram,[34] V.A. Bezzubov,[32] P.C. Bhat,[12] V. Bhatnagar,[31] M. Bhattacharjee,[11] A. Bischoff,[7] N. Biswas,[30] G. Blazey,[12] S. Blessing,[13] P. Bloom,[5] A. Boehnlein,[12] N.I. Bojko,[32] F. Borcherding,[12] J. Borders,[35] C. Boswell,[7] A. Brandt,[12] R. Brock,[23] A. Bross,[12] D. Buchholz,[29] V.S. Burtovoi,[32] J.M. Butler,[12] D. Casey,[35] H. Castilla-Valdez,[9] D. Chakraborty,[38] S.-M. Chang,[27] S.V. Chekulaev,[32] L.-P. Chen,[20] W. Chen,[38] L. Chevalier,[36] S. Chopra,[31] B.C. Choudhary,[7] J.H. Christenson,[12] M. Chung,[15] D. Claes,[38] A.R. Clark,[20] W.G. Cobau,[21] J. Cochran,[7] W.E. Cooper,[12] C. Cretsinger,[35] D. Cullen-Vidal,[4] M. Cummings,[14] D. Cutts,[4] O.I. Dahl,[20] K. De,[41] M. Demarteau,[12] R. Demina,[27] K. Denisenko,[12] N. Denisenko,[12] D. Denisov,[12] S.P. Denisov,[32] W. Dharmaratna,[13] H.T. Diehl,[12] M. Diesburg,[12] G. Di Loreto,[23] R. Dixon,[12] P. Draper,[41] J. Drinkard,[6] Y. Ducros,[36] S.R. Dugad,[40] S. Durston-Johnson,[35] D. Edmunds,[23] A.O. Efimov,[32] J. Ellison,[7] V.D. Elvira,[12,‡] R. Engelmann,[38] S. Eno,[21] G. Eppley,[34] P. Ermolov,[24] O.V. Eroshin,[32] V.N. Evdokimov,[32] S. Fahey,[23] T. Fahland,[4] M. Fatyga,[3] M.K. Fatyga,[35] J. Featherly,[3] S. Feher,[38] D. Fein,[2] T. Ferbel,[35] G. Finocchiaro,[38] H.E. Fisk,[12] Yu. Fisyak,[24] E. Flattum,[23] G.E. Forden,[2] M. Fortner,[28] K.C. Frame,[23] P. Franzini,[10] S. Fredriksen,[39] S. Fuess,[12] A.N. Galjaev,[32] E. Gallas,[41] C.S. Gao,[12,*] S. Gao,[12,*] T.L. Geld,[23] R.J. Genik II,[23] K. Genser,[12] C.E. Gerber,[12,§] B. Gibbard,[3] V. Glebov,[35] S. Glenn,[5] B. Gobbi,[29] M. Goforth,[13] A. Goldschmidt,[20] B. Gomez,[1] P.I. Goncharov,[32] H. Gordon,[3] L.T. Goss,[42] N. Graf,[3] P.D. Grannis,[38] D.R. Green,[12]

J. Green,[28] H. Greenlee,[12] G. Griffin,[6] N. Grossman,[12] P. Grudberg,[20] S. Grünendahl,[35]
W. Gu,[12,*] J.A. Guida,[38] J.M. Guida,[3] W. Guryn,[3] S.N. Gurzhiev,[32] Y.E. Gutnikov,[32]
N.J. Hadley,[21] H. Haggerty,[12] S. Hagopian,[13] V. Hagopian,[13] K.S. Hahn,[35] R.E. Hall,[6]
S. Hansen,[12] R. Hatcher,[23] J.M. Hauptman,[17] D. Hedin,[28] A.P. Heinson,[7] U. Heintz,[12]
R. Hernández-Montoya,[9] T. Heuring,[13] R. Hirosky,[13] J.D. Hobbs,[12] B. Hoeneisen,[1,¶]
J.S. Hoftun,[4] F. Hsieh,[22] Ting Hu,[38] Tong Hu,[16] T. Huehn,[7] S. Igarashi,[12] A.S. Ito,[12]
E. James,[2] J. Jaques,[30] S.A. Jerger,[23] J.Z.-Y. Jiang,[38] T. Joffe-Minor,[29] H. Johari,[27]
K. Johns,[2] M. Johnson,[12] H. Johnstad,[39] A. Jonckheere,[12] M. Jones,[14] H. Jöstlein,[12]
S.Y. Jun,[29] C.K. Jung,[38] S. Kahn,[3] J.S. Kang,[18] R. Kehoe,[30] M.L. Kelly,[30] A. Kernan,[7]
L. Kerth,[20] C.L. Kim,[18] S.K. Kim,[37] A. Klatchko,[13] B. Klima,[12] B.I. Klochkov,[32]
C. Klopfenstein,[38] V.I. Klyukhin,[32] V.I. Kochetkov,[32] J.M. Kohli,[31] D. Koltick,[33]
A.V. Kostritskiy,[32] J. Kotcher,[3] J. Kourlas,[26] A.V. Kozelov,[32] E.A. Kozlovski,[32]
M.R. Krishnaswamy,[40] S. Krzywdzinski,[12] S. Kunori,[21] S. Lami,[38] G. Landsberg,[38]
R.E. Lanou,[4] J-F. Lebrat,[36] A. Leflat,[24] H. Li,[38] J. Li,[41] Y.K. Li,[29] Q.Z. Li-Demarteau,[12]
J.G.R. Lima,[8] D. Lincoln,[22] S.L. Linn,[13] J. Linnemann,[23] R. Lipton,[12] Y.C. Liu,[29]
F. Lobkowicz,[35] S.C. Loken,[20] S. Lökös,[38] L. Lueking,[12] A.L. Lyon,[21] A.K.A. Maciel,[8]
R.J. Madaras,[20] R. Madden,[13] I.V. Mandrichenko,[32] Ph. Mangeot,[36] S. Mani,[5]
B. Mansoulié,[36] H.S. Mao,[12,*] S. Margulies,[15] R. Markeloff,[28] L. Markosky,[2] T. Marshall,[16]
M.I. Martin,[12] M. Marx,[38] B. May,[29] A.A. Mayorov,[32] R. McCarthy,[38] T. McKibben,[15]
J. McKinley,[23] H.L. Melanson,[12] J.R.T. de Mello Neto,[8] K.W. Merritt,[12] H. Miettinen,[34]
A. Milder,[2] C. Milner,[39] A. Mincer,[26] J.M. de Miranda,[8] C.S. Mishra,[12]
M. Mohammadi-Baarmand,[38] N. Mokhov,[12] N.K. Mondal,[40] H.E. Montgomery,[12]
P. Mooney,[1] M. Mudan,[26] C. Murphy,[16] C.T. Murphy,[12] F. Nang,[4] M. Narain,[12]
V.S. Narasimham,[40] A. Narayanan,[2] H.A. Neal,[22] J.P. Negret,[1] E. Neis,[22] P. Nemethy,[26]
D. Nešić,[4] D. Norman,[42] L. Oesch,[22] V. Oguri,[8] E. Oltman,[20] N. Oshima,[12] D. Owen,[23]
P. Padley,[34] M. Pang,[17] A. Para,[12] C.H. Park,[12] Y.M. Park,[19] R. Partridge,[4] N. Parua,[40]
M. Paterno,[35] J. Perkins,[41] A. Peryshkin,[12] M. Peters,[14] H. Piekarz,[13] Y. Pischalnikov,[33]
A. Pluquet,[36] V.M. Podstavkov,[32] B.G. Pope,[23] H.B. Prosper,[13] S. Protopopescu,[3]

D. Pušeljić,[20] J. Qian,[22] P.Z. Quintas,[12] R. Raja,[12] S. Rajagopalan,[38] O. Ramirez,[15]
M.V.S. Rao,[40] P.A. Rapidis,[12] L. Rasmussen,[38] A.L. Read,[12] S. Reucroft,[27]
M. Rijssenbeek,[38] T. Rockwell,[23] N.A. Roe,[20] J.M.R. Roldan,[1] P. Rubinov,[38] R. Ruchti,[30]
S. Rusin,[24] J. Rutherfoord,[2] A. Santoro,[8] L. Sawyer,[41] R.D. Schamberger,[38]
H. Schellman,[29] D. Schmid,[39] J. Sculli,[26] E. Shabalina,[24] C. Shaffer,[13] H.C. Shankar,[40]
R.K. Shivpuri,[11] M. Shupe,[2] J.B. Singh,[31] V. Sirotenko,[28] W. Smart,[12] A. Smith,[2]
R.P. Smith,[12] R. Snihur,[29] G.R. Snow,[25] S. Snyder,[38] J. Solomon,[15] P.M. Sood,[31]
M. Sosebee,[41] M. Souza,[8] A.L. Spadafora,[20] R.W. Stephens,[41] M.L. Stevenson,[20]
D. Stewart,[22] F. Stocker,[39] D.A. Stoianova,[32] D. Stoker,[6] K. Streets,[26] M. Strovink,[20]
A. Taketani,[12] P. Tamburello,[21] J. Tarazi,[6] M. Tartaglia,[12] T.L. Taylor,[29] J. Teiger,[36]
J. Thompson,[21] T.G. Trippe,[20] P.M. Tuts,[10] N. Varelas,[23] E.W. Varnes,[20]
P.R.G. Virador,[20] D. Vititoe,[2] A.A. Volkov,[32] A.P. Vorobiev,[32] H.D. Wahl,[13] J. Wang,[12,*]
L.Z. Wang,[12,*] J. Warchol,[30] M. Wayne,[30] H. Weerts,[23] W.A. Wenzel,[20] A. White,[41]
J.T. White,[42] J.A. Wightman,[17] J. Wilcox,[27] S. Willis,[28] S.J. Wimpenny,[7]
J.V.D. Wirjawan,[42] Z. Wolf,[39] J. Womersley,[12] E. Won,[35] D.R. Wood,[12] H. Xu,[4]
R. Yamada,[12] P. Yamin,[3] C. Yanagisawa,[38] J. Yang,[26] T. Yasuda,[27] C. Yoshikawa,[14]
S. Youssef,[13] J. Yu,[35] Y. Yu,[37] Y. Zhang,[12,*] Y.H. Zhou,[12,*] Q. Zhu,[26] Y.S. Zhu,[12,*]
Z.H. Zhu,[35] D. Zieminska,[16] A. Zieminski,[16] A. Zinchenko,[17] and A. Zylberstejn[36]

(DØ Collaboration)

[1] *Universidad de los Andes, Bogota, Colombia*

[2] *University of Arizona, Tucson, Arizona 85721*

[3] *Brookhaven National Laboratory, Upton, New York 11973*

[4] *Brown University, Providence, Rhode Island 02912*

[5] *University of California, Davis, California 95616*

[6] *University of California, Irvine, California 92717*

[7] *University of California, Riverside, California 92521*

[8]*LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

[9]*CINVESTAV, Mexico City, Mexico*

[10]*Columbia University, New York, New York 10027*

[11]*Delhi University, Delhi, India 110007*

[12]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[13]*Florida State University, Tallahassee, Florida 32306*

[14]*University of Hawaii, Honolulu, Hawaii 96822*

[15]*University of Illinois at Chicago, Chicago, Illinois 60607*

[16]*Indiana University, Bloomington, Indiana 47405*

[17]*Iowa State University, Ames, Iowa 50011*

[18]*Korea University, Seoul, Korea*

[19]*Kyungsung University, Pusan, Korea*

[20]*Lawrence Berkeley Laboratory and University of California, Berkeley, California 94720*

[21]*University of Maryland, College Park, Maryland 20742*

[22]*University of Michigan, Ann Arbor, Michigan 48109*

[23]*Michigan State University, East Lansing, Michigan 48824*

[24]*Moscow State University, Moscow, Russia*

[25]*University of Nebraska, Lincoln, Nebraska 68588*

[26]*New York University, New York, New York 10003*

[27]*Northeastern University, Boston, Massachusetts 02115*

[28]*Northern Illinois University, DeKalb, Illinois 60115*

[29]*Northwestern University, Evanston, Illinois 60208*

[30]*University of Notre Dame, Notre Dame, Indiana 46556*

[31]*University of Panjab, Chandigarh 16-00-14, India*

[32]*Institute for High Energy Physics, 142-284 Protvino, Russia*

[33]*Purdue University, West Lafayette, Indiana 47907*

[34]*Rice University, Houston, Texas 77251*

[35]*University of Rochester, Rochester, New York 14627*

[36] *CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, France*

[37] *Seoul National University, Seoul, Korea*

[38] *State University of New York, Stony Brook, New York 11794*

[39] *SSC Laboratory, Dallas, Texas 75237*

[40] *Tata Institute of Fundamental Research, Colaba, Bombay 400005, India*

[41] *University of Texas, Arlington, Texas 76019*

[42] *Texas A&M University, College Station, Texas 77843*

Abstract

The ratio of the number of $W + 1$ jet to $W + 0$ jet events is measured in the DØ detector using data from the 1992-93 Tevatron Collider run. The $W \to e\nu$ channel is used with a minimum jet E_T cutoff of 25 GeV. Using the measured ratio and Next-to-Leading order QCD predictions, we find the strong coupling constant at the renormalization scale M_W to be $\alpha_s(M_W) = 0.129 \pm 0.015$ and $\alpha_s(M_W) = 0.139 \pm 0.017$ for the MRS(D_0') and CTEQ3M parton distributions, respectively. Generally, our data prefer a larger value of α_s than that used internally in parton distributions.

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The running coupling constant α_s is a fundamental expansion parameter which sets the strength of all strong interactions. Of particular interest in the current study is the fact that the probability of producing jets in association with a W boson is dependent on the value of α_s. We report here the results of extracting the value of α_s from an examination of the ratio, $\mathcal{R}$, of $W+1$ jet to $W+\ 0$ jet cross sections. A similar technique, based on tree level calculations, has been used by the UA2 [1] and UA1 experiments [2]. Determination of α_s at any given value of the renormalization scale μ_R provides knowledge of the coupling at all other μ_R, and the expected dependence of α_s on μ_R has been confirmed by other experiments over the range 1 GeV $< \ \mu_R \ <$ 91 GeV [3].

In leading-order (LO) QCD, $\mathcal{R}$ is proportional to α_s. However, the cross sections computed at LO suffer from relatively large normalization uncertainties due to the lack of higher order corrections. Recent next-to-leading order (NLO) predictions [4] of the $W+0$ jet and $W+1$ jet cross sections show significantly reduced μ_R dependence and differ from LO predictions by about 10% for μ_R equal to the W mass (M_W) [5].

We present a determination of α_s at $\mu_R = M_W$ from an experimental measurement of the ratio, $\mathcal{R}_{\rm meas}$, using the DØ detector at the Fermilab Tevatron $\overline{p}p$ Collider at $\sqrt{s} = 1.8$ TeV. We utilize 9770 $W \rightarrow e\nu$ candidates collected during the 1992 - 93 collider run. This analysis is based upon the comparison of $\mathcal{R}_{\rm meas}$ with the NLO theoretical predictions [6].

The DØ detector is described in detail elsewhere [7]. The detector elements relevant to this analysis are the tracking system and the uranium liquid-argon sampling calorimeter. The tracking system, which has no magnetic field, covers a range of pseudorapidity, η [8], from -3.0 to 3.0. The calorimeter's homogeneous response and hermetic coverage out to $|\eta| \sim 4$ provide excellent measurement of electron and jet energies, as well as missing transverse energy ($\not\!\!E_T$), over the full azimuth (ϕ). The calorimeter is finely segmented in both the longitudinal and transverse directions, giving enhanced electron identification. The electron energy resolution is $15\%/\sqrt{E(\mathrm{GeV})}$ and the jet transverse energy (E_T) resolution is $\sim 80\%/\sqrt{E_T(\mathrm{GeV})}$.

For this analysis, we use a hardware trigger which requires events with a minimum E_T of

10 GeV in an electromagnetic (EM) calorimeter trigger tower of size 0.2×0.2 in η-ϕ space, covering $|\eta| < 3.2$. Events satisfying the hardware trigger are subjected to a software trigger which requires the event to have $\not\!\!E_T > 20$ GeV and to have an electron candidate which has transverse energy (E_T^e) greater than 20 GeV and passes preliminary shower shape and isolation cuts.

The offline selection of the $W \to e\nu$ event sample requires $\not\!\!E_T > 25$ GeV and an electron with $E_T^e > 25$ GeV which satisfies three electron quality criteria. The first involves the isolation fraction which is defined as $f_{\rm iso} = [E(0.4) - E_{\rm EM}(0.2)]/E_{\rm EM}(0.2)$, where $E(0.4)$ is the total energy within a cone of radius 0.4 ($\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) centered around the electron, and $E_{\rm EM}(0.2)$ is the EM energy within $\Delta R = 0.2$. A cut of $f_{\rm iso} < 0.15$ is imposed to require that the electron is isolated from other sources of energy in the event. The second criterion is that the calorimeter energy deposition of the electron has a matching charged track. Finally, a cut is imposed on the χ^2 value of the energy cluster to ensure that its shape is consistent with that of an electron. This value of χ^2 is computed using a 41 dimensional energy covariance matrix [9], which has the mean cell energy depositions of a reference electron shower as its elements, preserving their correlations.

Given the nature of $\mathcal{R}_{\rm meas}$, it is advantageous, in minimizing systematic uncertainties, to have the electron selection efficiency be the same for events with and without an associated jet. The electron selection criteria applied to the $W \to e\nu$ candidates preclude the use of this data sample for estimating the selection efficiency because the only electron in the events is already subjected to the selection criteria. Therefore, we use $Z(\to e^+e^-) + 0$ jet and $Z + 1$ jet candidates from actual data, where only one of the two electrons is required to pass the selection criteria. The electron selection efficiency is then measured by imposing the selection criteria on the other electron. From this study, the electron selection efficiency is found to be the same for these jet multiplicities (0 jets and 1 jet) to within 2%.

Jets in the events are identified with a fixed cone algorithm using a radius $\Delta R = 0.7$. The jet reconstruction efficiency is found to be better than 99% for jets with $E_T > 20$ GeV, based on a Monte Carlo study [10]. The jet E_T is corrected for the calorimeter response, out-of-cone showering, and the underlying event contribution. The jet energy scale correction [11] is obtained by using events with photon+jet final states. In these events, the photon candidate is taken to balance the remaining partons in the event kinematically. The components of the transverse momentum imbalance due to the mismeasurement in hadronic jet energy are then corrected using the $\not\!\!E_T$ projection on the photon candidate axis. The typical size of the correction is (16±5)% at 25 GeV and (24±5)% at 100 GeV. The jets are required to have a minimum transverse energy (E_T^{min}) of 25 GeV. Before background subtraction, 5736 $W + 0$ jet events have the electron in the central region ($|\eta_e| < 1.2$) and 3083 events have the electron in the forward region ($|\eta_e| > 1.2$). The corresponding numbers of events with one jet are 511 and 284 events, respectively.

The largest background to the $W \to e\nu$ production comes from multijet processes. A jet from a multijet event may pass all electron selection criteria due to fluctuations in fragmentation. Significant $\not\!\!E_T$ may also be associated with multijet events due to shower fluctuations or calorimeter imperfections. Occasionally a multijet event has both significant $\not\!\!E_T$ and a jet imitating an electron and thereby simulate a $W \to e\nu$ event.

The fractional background from multijet events is estimated using the $\not\!\!E_T$ distributions from data for events that pass an inclusive electron trigger ($E_T^e > 20$ GeV). The sample is separated into two subsets. The first subset consists of events failing all three of the electron quality criteria ($f_{\rm iso}$, track matching, and χ^2). Real electrons from W decays contribute negligibly to this subset. The second subset consists of events which pass the three electron quality criteria. This subset includes both backgrounds from multijet events and real W events. The histogram in Fig. 1 represents the $\not\!\!E_T$ distribution of events with electrons satisfying the three electron quality criteria (signal + background) and the solid circles represent the other subset (background). A clear separation between signal and background above $\not\!\!E_T = 20$ GeV is evident because the $\not\!\!E_T$ due to the neutrino in W decay peaks near 40 GeV and far less $\not\!\!E_T$ is expected in true multijet events. The shapes of the two distributions agree well for $\not\!\!E_T < 15$ GeV. The background distribution for $\not\!\!E_T > 25$ GeV is used to estimate the contamination of the W sample from multijet processes.

For events with an electron in the central region, the background is $3.0\% \pm 0.6\%(\text{stat} + \text{sys})$ for $W + 0$ jet and $(19.3 \pm 4.3)\%$ for $W + 1$ jet events. The background for events with an electron in the forward region is $(13.3 \pm 1.6)\%$ for $W + 0$ jet and $(52.6 \pm 5.2)\%$ for $W + 1$ jet events. The uncertainties reflect systematic and statistical errors added in quadrature. The statistical uncertainty is the dominant source of error in estimating the background.

Additional sources of background to $W \to e\nu$ production are from electroweak processes which either are improperly identified in the detector or have a signature identical to that of $W \to e\nu$ production. The electroweak processes we considered are $Z \to e^+e^-$ and $q\bar{q} \to \gamma^* \to e^+e^-$ where one of the electrons is lost, and $Z \to \tau^+\tau^-$ where one of the τ's decays to $e\nu\bar{\nu}$ and the other decays hadronically. We use Monte Carlo event samples to estimate the background contamination from these sources, and find the level of contamination to be less than 3% of the signal for both $W + 0$ jet and $W + 1$ jet events. The process $W \to \tau\nu$ (where $\tau \to e\nu\bar{\nu}$) is considered as part of the signal because the associated jet production is independent of the W decay mode.

The number of $W + 0$ jet events, after subtracting backgrounds from multijet and electroweak processes, is $8200 \pm 94(\text{stat}) \pm 61(\text{sys})$, and the number of $W + 1$ jet events is $532 \pm 28(\text{stat}) \pm 49(\text{sys})$. The resulting experimental ratio of the number of $W + 1$ jet events to $W + 0$ jet events is $\mathcal{R}_{\text{exp}} = 0.065 \pm 0.003(\text{stat}) \pm 0.007(\text{sys})$. The dominant systematic error is from the jet energy scale uncertainty. This is due to the rapidly falling shape of the jet E_T spectrum and the resulting sensitivity to the E_T^{min} cutoff. This systematic error is obtained by repeating the complete analysis, varying the jet energy scale correction within errors.

The NLO QCD predictions [4] for $W + 0$ jet and $W + 1$ jet cross sections enable parameterizations of each cross section as a power series in α_s. The theoretical predictions, using the $\overline{\text{MS}}$ scheme, take into account the effect of experimental jet energy resolution, as well as the impact of the lepton isolation criteria and other experimental constraints. The cross section for $W + n$ jets is parameterized as: $\sigma_{W+n\text{jets}} = \alpha_s^n(A_n + \alpha_s B_n)$ for $n = 0$ or 1.

The coefficients A_1 and B_0 depend on E_T^{min} of the jet and B_1 depends on E_T^{min}, the choice of jet cone radius ΔR, and μ_R. The coefficients are computed for a given set of parton distribution function (pdf) which is evolved to the scale M_W. The evolution is carried out using the value for Λ_{QCD} associated with each pdf. This Λ_{QCD} value corresponds to a value of α_s, which is calculated at the scale of M_W using the second order expression for the running coupling constant and is labeled as α_s^{pdf} in Table I. Figure 2 shows $\mathcal{R}_{\rm meas}$ with its uncertainty given by the shaded area and symbols representing the predictions for various pdf's [12–14] at $\alpha_s = \alpha_s^{pdf}(M_W)$. The lines in Fig. 2 represent the predicted ratios, as a function of α_s, for the CTEQ3M [12] and MRS(D_0') [13] pdf's. There is an error associated with Monte Carlo statistics which is 100% correlated between the predictions. This error is shown in Fig. 2 for the prediction with CTEQ2ML pdf only. In these predictions the strong coupling constant is only varied in the hard partonic cross section, leaving α_s in the parton distributions fixed. The intercept of $\mathcal{R}_{\rm meas}$ with the theoretical prediction yields the value of α_s to NLO. This measurement of α_s should, in principle, agree with the α_s^{pdf} value evolved from the low energy data if all data are consistent.

In previous analysis [1] α_s has been determined by refitting a particular pdf with different values for α_s^{pdf}. Different choices for α_s in *both* pdf and hard partonic cross section result in a series of points in the $\mathcal{R}$ vs. α_s plane, which are connected by a line whose intercept with $\mathcal{R}_{\rm meas}$ yields a determination of α_s. We have attempted this and find that the slope of the obtained lines depends strongly on the chosen set of pdf. A complete treatment would require either pdf's with error estimates or full fits using the primary data and the data from this measurement. This is beyond the scope of this analysis and we therefore quote α_s values for different parton distributions.

Table I summarizes the values of α_s, at $\mu_R = M_W$, for various pdf's along with the uncertainties. The different sources contributing to the uncertainty in the determination are summarized in Table II for the CTEQ2M parton distribution. The error $\Delta\alpha_s$ in Table I is the quadratic sum of all these uncertainties. We do not assign an uncertainty due to the choice of μ_R because the variation in the $W + 1$ jet cross section is less than 2% for

$M_W/2 < \mu_R < 3M_W$ [4,15]. The dependence of α_s on E_T^{min} has been studied in the range 25 GeV $< E_T^{min} <$ 60 GeV [6] and the resulting values of α_s are independent of E_T^{min}.

Using the CTEQ3M and MRS(D$'_0$) pdf's, we obtain $\alpha_s(M_W) = 0.139 \pm 0.017$ and $\alpha_s(M_W) = 0.129 \pm 0.015$, respectively. These two results happen to represent the extreme values found. In general, our high energy data prefer a larger value of α_s than the values used in the pdf's which are mainly determined from fits to low energy data.

In summary, we have determined the strong coupling constant $\alpha_s(M_W)$, using NLO perturbation theory, from the ratio of the $W + 1$ jet to $W + 0$ jet cross sections. The determination of α_s in $\bar{p}p$ collisions depends on the knowledge of the parton distribution in the proton. Therefore, α_s has been extracted for a variety of parton distributions. We obtain higher values of α_s than those determined in all of the parton distributions used; the discrepency is at about the one standard deviation level.

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REFERENCES

* Visitor from IHEP, Beijing, China.

‡ Visitor from CONICET, Argentina.

§ Visitor from Universidad de Buenos Aires, Argentina.

¶ Visitor from Univ. San Francisco de Quito, Ecuador.

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TABLES

TABLE I. Values of α_s for various parton distributions [12–14].

pdf	$\alpha_s^{pdf}(M_W)$	$\alpha_s(M_W) \pm \Delta\alpha_s$
CTEQ2M	0.112	0.134 ± 0.016
CTEQ2ML	0.119	0.139 ± 0.017
CTEQ2MF	0.113	0.132 ± 0.015
CTEQ2MS	0.113	0.131 ± 0.015
CTEQ3M	0.114	0.139 ± 0.017
MRS(D_0')	0.113	0.129 ± 0.015
MRS(S_0')	0.113	0.129 ± 0.015
MRS(D_-')	0.113	0.136 ± 0.016
GRV	0.111	0.129 ± 0.015

TABLE II. Summary of uncertainties in α_s for the CTEQ2M parton distribution.

Source	$\Delta\alpha_s$
Experimental statistics	0.005
Jet energy scale correction	0.013
Jet reconstruction efficiency	0.002
Jet energy resolution	0.005
Monte Carlo statistics	0.005
Total $\Delta\alpha_s$	0.016

FIGURES

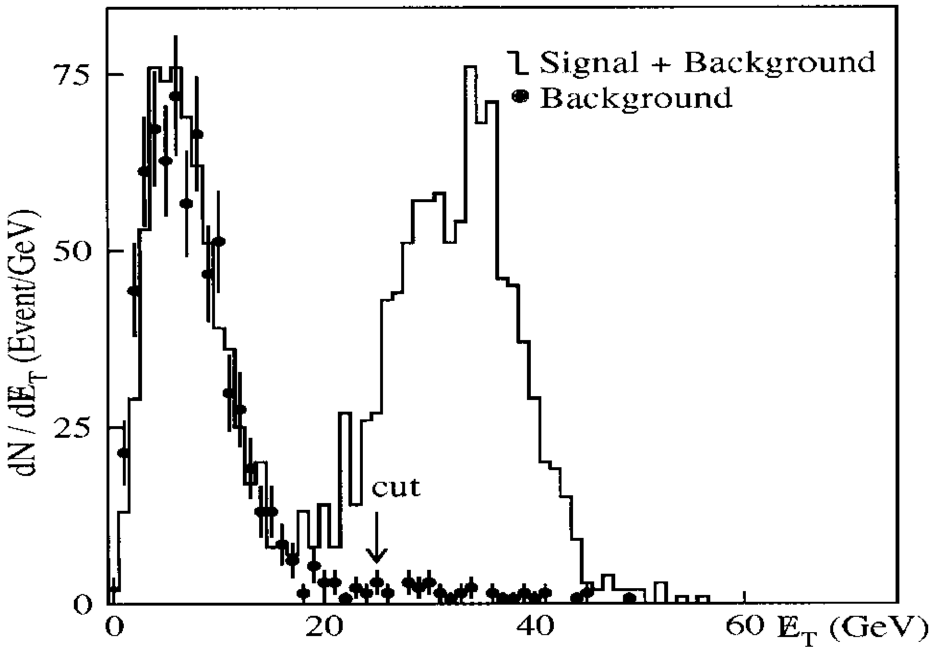

FIG. 1. $\not{E}_T$ distributions for $W+0$ jet events with the electron in the central region, $|\eta_e| < 1.2$. The histogram represents the signal plus background and solid circles indicate the background. The two distributions are normalized using the number of events in the region $\not{E}_T < 15$ GeV. The error bars represent statistical errors only.

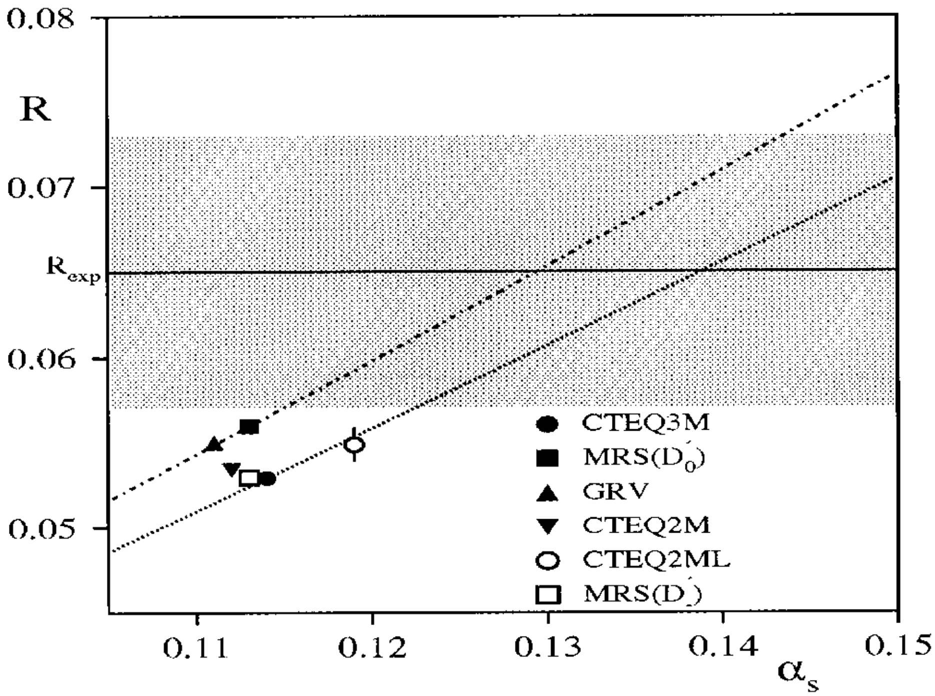

FIG. 2. $\mathcal{R}$ vs α_s for CTEQ3M and MRS(D_0') pdf's. All other pdf's correspond to lines with very similar slopes and are contained in the region between the two predictions shown.